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## THREE-DIMENSIONAL SEISMIC MODELING

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

cont → As a first test of the entire seismic modeling system, ~~we instrumented~~ <sup>was instrumented</sup> a 2 x 2 x 1 ft foam block with three surface motion transducers, two strain gages, and three ytterbium foil stress gages and ~~loaded~~ <sup>was loaded</sup> the block by detonation of our small, spherical explosive source. ~~We recorded~~ <sup>about</sup> peak surface displacements of ~~10  $\mu$ m~~ <sup>micrometers</sup> and peak surface lateral strains of ~~10<sup>-4</sup>~~ <sup>about 0.0001</sup>, both with better than 1% precision. <sup>were recorded.</sup> The stress gage recorded peak stresses of ~~5~~ <sup>about</sup> bars, but lacked good precision in this very low stress region.

Preliminary studies were made of producing a low-amplitude (on the order of 100 bar) plane wave loading over a wide area for future seismic modeling experiments. The use of a low-energy explosive mixture of PETN powder and hollow plastic spheres, separated from the surface to be loaded by an orifice plate, shows good promise. ↑

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#### ACKNOWLEDGMENTS

We are indebted to Mr. Phil Bentley for his work in designing, building, and testing the circuitry for the capacitive surface motion gage, and to Dr. Ker Thomson of Air Force Geophysics Laboratory for giving support and direction to this program.

## I SUMMARY

During this contract period, we extended the development of three-dimensional seismic modeling techniques to the point where actual seismic modeling experiments can be readily performed in the laboratory with excellent prospects of obtaining high precision data. Our choice for the seismic modeling material, syntactic foam, has demonstrated its abilities as a homogeneous, isotropic propagation medium into which transducers can be easily implanted for use in recording elastic response to repeated loadings. Our newly developed capacitive surface motion gage has demonstrated extremely high sensitivity (up to 1 volt signal/0.001 inch displacement) and precision (to the nearest one or two micro-inches) in an actual seismic modeling test (see Figure 8). Standard thin foil strain gages also performed with excellent precision on the same test (see Figure 9). Our ytterbium stress gages, on the other hand, did not perform adequately at the very low stresses encountered (5 bar); an alternative scheme will need to be devised if precise stress measurements are required in this region.

The capacitive surface motion gage was tested in a plane geometry: we measured the perpendicular displacement of a flat surface. Other geometries amenable to capacitor surface motion gage techniques may occur in seismic modeling experiments. For example, if the elastic response of the inside surfaces of a cylindrical cavity is of interest, a cylindrical surface motion gage can be used to determine the radial expansion and contraction of the cylinder walls. Such a gage could be orders of magnitude more sensitive than strain gages attached to the inside walls of the cylindrical cavity in the hoop direction. The same circuitry could be used as in the planar surface motion gage. Only the geometry of the plates and the physical locations of some of the electronic components would need to be changed. Furthermore, the same experiment could use several gages of different geometries.

In conclusion, we have by no means exhausted the development of three-dimensional seismic modeling techniques. Yet to be developed is the low-amplitude plane-wave loading source, although a promising design for such a source is discussed in this report (Section IIIA). Further work is needed to develop a stress gage that will yield precise results in the low pressure region around 5 bars. However, we now have a system that has been successfully tested and will yield precise strain and surface motion data for a very wide range of geometries, loading conditions, and response frequencies.

## II INTRODUCTION

For the past  $2\frac{1}{2}$  years, SRI has conducted a program for the Air Force Geophysics Laboratory to develop techniques that would allow three-dimensional seismic modeling experiments to be performed on a size scale convenient for the laboratory. The ultimate goal of this program is to use these techniques to model and characterize the elastic response of surface and subsurface structures, such as cylindrical cavities, to geophysical excitations.

During the first 18 months, we successfully completed:<sup>1</sup>

- Selection and testing of candidate seismic modeling materials for use as the propagation medium
- Development and testing of a small, spherically symmetric explosive source of reliably uniform output that is encapsulated so as to allow relatively easy and safe handling and detonating procedures.
- Construction of a biaxial prestressing frame that will allow static loading of the seismic modeling medium independently in two directions.

Our continued seismic modeling technique development during the past year originally included the following tasks:

- Task (1) Develop the technique to routinely produce the spherically explosive source and produce one hundred of these sources for AFGL.
- Task (2) Select a homogeneous, isotropic material to be used as the modeling medium, and extend our techniques to produce large blocks of such a material with very repeatable properties.
- Task (3) Develop and test transducer techniques for reliable measurement of elastic waves generated in the seismic modeling medium.

Task (1) was later amended to eliminate the production of the one hundred sources for AFGL, and instead to begin preliminary studies of methods for producing low-amplitude plane-wave loading over large areas for future seismic modeling experiments. During this contract period, we have emphasized Tasks (2) and (3).

The remainder of this report is organized as follows. In Section III we discuss in detail the explosive source development, the seismic modeling material, and our transducer development. Finally, in Section IV we describe an experimental test that combined many of the seismic modeling techniques developed thus far.

### III DEVELOPMENTAL PROGRAM

#### A. Explosive Sources for Seismic Modeling

The small, spherically symmetric explosive source, described in detail in last year's final report,<sup>1</sup> has not been further developed in this contract period. Approximately twelve of these sources, a few of which were stored for more than a year, have been detonated without a single failure.

A preliminary study was made of possible methods for producing planar loading over large areas, for use in future seismic modeling experiments. Since the amplitude of such a plane-wave must be below the tensile strength of the syntactic foam to avoid damage to the large foam block, we cannot use any of the standard high explosives, which produce pressures in the hundreds of kilobars. Recently, however, mixtures of PETN\* powder and tiny hollow plastic spheres have been used to produce detonations with peak pressure as low as 2 kbar, and these pressures have been further reduced by as much as two orders of magnitude by having the gaseous products of detonation of this explosive mixture expand through an orifice plate before it reaches the plane surface to be loaded.<sup>2</sup> With such a method, surface pressures below the syntactic foam tensile strength could be easily attained, and the geometry of the explosive mixture/orifice plate system could be used to tailor the rise time and decay time of the planar loading source. This technique should be investigated further.

#### B. Seismic Modeling Material

Under last year's contract we determined the properties required in a material intended for use as a seismic modeling propagation medium, and we narrowed our choice to syntactic foam and gypsum grout.<sup>1</sup> The foam was significantly more isotropic and homogeneous than the grout and more

\*Pentaerythritol tetranitrate ( $C_5H_8O_{12}N_4$ ).

repeatable in properties from one block to the next, but it was also more expensive. However, if large blocks of the modeling material could be instrumented with sensors and reused for many experiments, the initial cost of the material would be less consequential. Therefore, we selected syntactic foam as our seismic modeling material. The syntactic foam chosen was Eccofloat EF-38-A,<sup>\*</sup> which consists of 65- $\mu$ m-diameter hollow glass spheres in an epoxy resin. This strong but lightweight foam is available both in factory-made blocks of any desired shape and in a two-part castable kit.

We machined one factory-made block to the dimensions 1 x 2 x 2 ft for use as our principal, reusable modeling medium. The block has a density of 0.61 gm/cm<sup>3</sup> (density being the only wave propagation material property that could be easily measured in a block of that size) and has occasional voids of diameter less than 1 mm. We also obtained several cubic feet of the two-part castable kit, to be used to cast blocks for preliminary experiments, to test material properties of the foam, and to fill in the sections of the large factory-cast block that were removed for sensor emplacement.

By using both vibratory agitation and vacuum deaeration in the casting process, we were able to produce small blocks free of voids, having a density of 0.63 gm/cm<sup>3</sup>, approximately 3% higher than the large block. This small discrepancy should have a negligible effect on an actual experiment. Sound velocity measurements of the small blocks yielded a value of 2.31 mm/ $\mu$ sec for the longitudinal velocity and 0.99 mm/ $\mu$ sec for the shear wave velocity. Two uniaxial stress tensile tests showed the material failing at stresses of 143 and 164 bars, at tensile strains of 0.008 and 0.0092, respectively. This relatively low tensile strength places an upper limit on the amplitude of the loading, which can be inputted into the foam block without causing damage. However, this limit is well above what would be experienced in distant seismic excitation.

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<sup>\*</sup>Trademark, Emerson & Cuming, Inc., Flotation Products Division, Canton, Mass.

### C. Transducer Development

The goal of this phase of the contract was to develop transducer techniques for measuring elastic wave response in the seismic modeling medium, by either adapting existing gages or developing new ones. The most important parameter to be measured in seismic modeling experiments would be surface motion. Other important parameters are in-material stress, surface strains, and in-material strains. We expected little difficulty in adapting standard thin foil strain gages and piezo-resistant ytterbium foil stress gages for use in measuring strains and stresses, and therefore, concentrated on the problem of measuring surface motions.

For normal seismic measurements, a large assortment of seismometers is available for measuring surface motions. However these transducers do not work for seismic modeling, in which both distances and durations are scaled down by factors as large as several orders of magnitude. What is needed is a gage that will respond to high frequencies (up to  $\approx 1$  MHz); will be sensitive enough to record very minute motions; will occupy a small area on the surface, so that motion variations across the surface can be measured; and will apply negligible load to the surface, so that its presence will have a negligible effect on the surface motion.

We first investigated existing transducers to determine if any had the required specifications. We found that piezoelectric accelerometers had insufficiently high frequency responses and that even the smallest seismometers would cause unacceptably high surface loading.

We then studied the possibility of developing a gage suited especially for seismic modeling application and arrived at three different types of surface motion gage that would have an adequate high-frequency response:

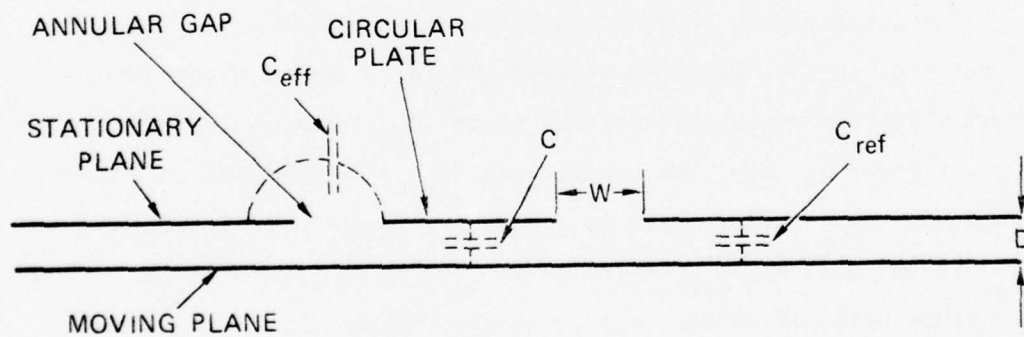
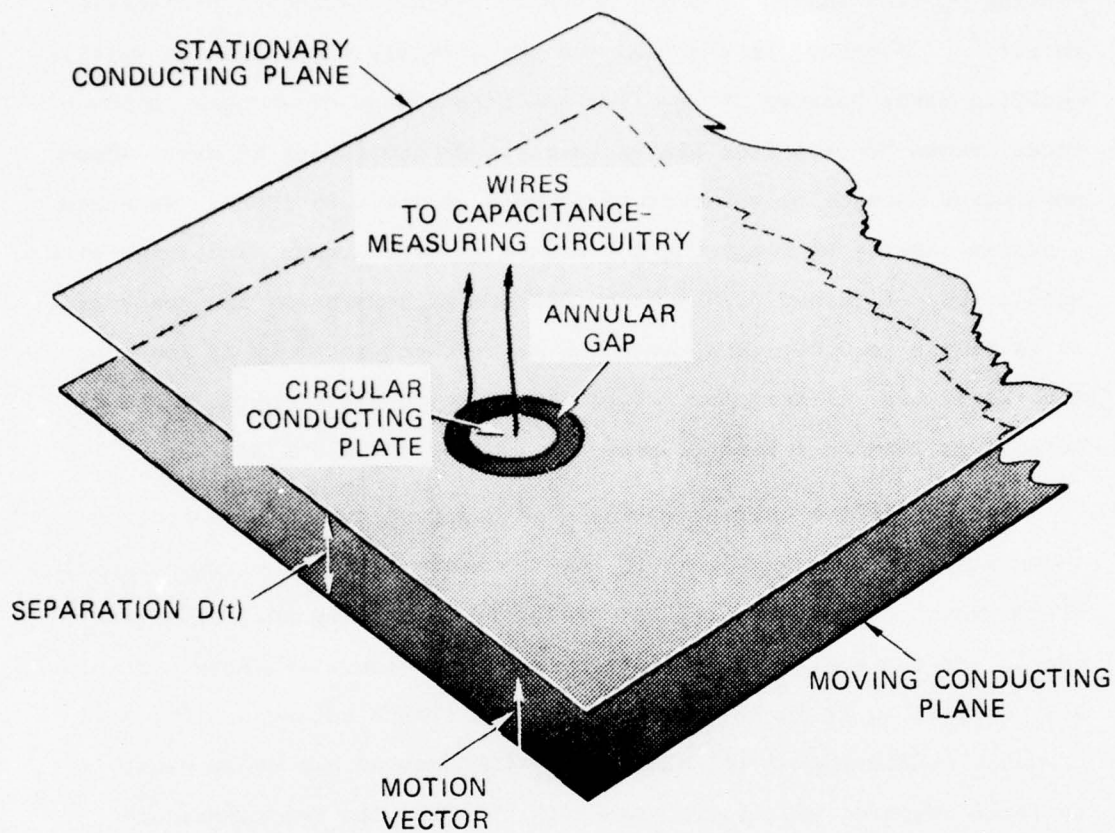
- (1) Magnetic induction velocity gage, in which a conductor moves with respect to a magnetic field. This type of gage has the advantage of being very simple in principle to calibrate. However, a serious disadvantage is that if several gages are to be used in close proximity, particularly, if they are used to measure motions in different directions, the magnetic fields for various gages will interact in a complicated way. Furthermore, large conductor lengths and high strength magnetic fields would be necessary to record the relatively low velocities produced (compared with those in high pressure shock wave experiments), resulting in high cost and complicated design to avoid surface loading.
- (2) Optical surface motion gages, including both laser interferometry and light reflectivity techniques. These systems have negligible surface loading, but require complicated alignment and calibration and involve questionable sensitivity (in the case of reflectivity techniques) and high cost (in the case of interferometry, for many data channels).
- (3) Capacitive displacement gage, in which the surface whose motion is to be measured acts on one plate of a parallel plate capacitor while the other plate remains fixed. This system has negligible surface loading (only a thin conducting foil need touch the surface) and simple calibration procedures. Furthermore, since the strengths of the electric fields in a parallel-plate capacitor are high only between the plates, little interaction would occur between two capacitors, provided they are separated by a distance this is large compared with the plate separation distance.

We selected the third method as the most promising alternative to be developed. In the literature, we found one reference to the use of

a capacitor circuit for measuring the velocity history of a plane conducting surface loaded by shock waves from a high-velocity projectile impact.<sup>2,3</sup> However, this method was not directly applicable to seismic modeling needs because it involved the measurement of changes in capacitance caused by capacitor plates (several square inches in area) whose separation changed by substantial amounts (up to 0.05 inch). We needed a system capable of measuring the change in capacitance associated with smaller plates (about 0.25 square inch) whose separation changed overall by as little as 0.001 inch, with the measurement accuracy at least as fine as 10  $\mu$ in. (1 part per 100 of the expected plate motion), and perhaps as fine as 1  $\mu$ in. (1 part per 1000 of the plate motion).

The capacitive surface motion gage designed during this program is shown schematically in Figure 1. At the bottom is the moving conducting plane, which could be a very thin sheet of conducting foil attached to the top of the surface whose motion is to be measured. Above this plane and parallel to it is the stationary plane, which consists of a small circular conducting plate, a nonconducting annular gap whose width (W) is large compared with the distance (D) between the two planes and a large reference conducting plane.

The capacitances between the large moving plate and the small circular plate (C), and that between the large moving plate and the equally large stationary reference plate ( $C_{ref}$ ) both vary inversely as a function of D. Now, the capacitance ( $C_{eff}$ ) between the reference plate and the circular plate is equivalent to the capacitance of C and  $C_{ref}$  in series. So,  $C_{eff} = (1/C + 1/C_{ref})^{-1}$ , but since the area of the reference plane (> 50 sq. in.) is so much larger than that of the circular plate ( $\approx$  0.2 sq. in.),  $C_{ref} \gg C$ . Therefore,  $C_{eff}$  becomes effectively equal to C, and we now have a method of measuring the capacitance between stationary and moving planes without any physical connection to the moving plane. We simply attach wires as shown in the



CROSS-SECTIONAL VIEW (Not to Scale)

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FIGURE 1 GEOMETRY OF CAPACITIVE SURFACE MOTION GAGE

figure, and by measuring the changes in  $C_{eff}$ , we can determine the changes in  $D$ .

The above discussion implicitly assumes that the moving plane is a rigid body, or rather, that  $D$  at a particular time ( $t$ ) is constant over the entire area of the plane. Now, let us relax that assumption by allowing  $D(t)$  to vary over the area of the plane. We can now place several small circular plates within the reference plane area and measure the capacitance between each of them and the one reference plane. Provided the spacing between the circular plates is large compared with  $D(t)$ , and that at no point actual physical contact occurs between the stationary and moving plates, we can now determine how  $D(t)$  varies as a function of position throughout the plane.

The problem thus far has been reduced to one of accurately measuring  $C_{eff}$  for each circular plate. The capacitance of a 0.5 inch-diameter circular parallel plate capacitor, whose plate separation is 0.01 inch, is approximately 5 picofarads (pf). If we want to measure total plate motions as small as 0.001 inch with 1% or 0.1% accuracy, then we need to be able to measure total capacitance changes as small as 0.5 pf to accuracies of 0.005 pf. or 0.0005 pf, respectively.

A common way to measure capacitance is to place the unknown capacitor in a bridge circuit, excite it with sinusoidal signal, and place known (calibrated) capacitors in the bridge to obtain a "null." In this case, however, the absolute value of the capacitance is not desired--only the variability of the capacitance as a function of time. The bridge components, therefore, are chosen for their nominal capacitance value, and the output voltage from the bridge is directly proportional to the change in the unknown capacitance over a certain range around the nominal null value. Where the capacitance value is very small (such as less than 10 pf), it is customary to use a high frequency (RF) excitation and then to envelope detect the output of the bridge circuit for conversion to a voltage analog.

The higher the frequency, the lower the bridge impedance, which makes detection and amplification of the different signals easier.

To measure very fast motions, the capacitor bridge and detector circuitry must have adequate bandwidth to respond to rapid changes in capacitance. We estimated that elastic waves propagating through syntactic foam in a seismic modeling experiment would have risetimes no faster than about 1  $\mu$ sec. Therefore, the capacitance bridge excitation frequency needs to be greater than 5 MHz to give an adequate sampling rate for the fastest risetime signal. However, because of filtering requirements (to remove the carrier wave itself) and because the carrier waves on different channels must have frequency differences greater than 1 MHz (so that crosstalk beat frequencies will also be removed by the filtering process), we selected carrier frequencies in the range 8 to 20 MHz.

After testing several different configurations for the capacitive gage electronics, we settled on the one shown schematically in Figure 2. The five principal parts of the circuitry are an adjustable frequency RF oscillator to provide the carrier wave, a transistor amplifier to augment the carrier wave amplitude, an isolation transformer, the capacitor bridge with an adjustable reference capacitor, and a detector/amplifier to separate the signal from the RF carrier wave and boost the signal for recording purposes. Power to the circuit is provided by two 15-volt dc power supplies. The reference capacitor is adjusted to be similar to the capacitance of the surface motion gage prior to the first motion, so that the bridge is close to its null point and therefore in its linear operating region. Subsequent change in the capacitance of the gage leads to an unbalance in the bridge circuit, which is rectified and amplified to yield a signal directly proportional to the RF signal difference across the bridge. The output signal is fed through a low-pass filter, which further diminishes the magnitude of the carrier



wave, while allowing signals of frequency less than 1 MHz to pass through undiminished.

The signal bandwidth of this circuit is established by the response limit of the operational amplifier, about 500 kHz. This is adequate to meet the requirements for a 1  $\mu$ sec rise time. The noise level is established by the RF oscillator and operational amplifier. The dynamic range of the system is greater than 80 dB, from the noise floor of  $\approx 1$  mV (assuming the RF oscillator has an amplitude stability of better than 1%) to the amplifier output limit of 10 volts. Since the output sensitivity can be as high as 1 volt/0.001 inch motion, (as determined by calibration, discussed below), the signal-to-noise ratio for a motion of 0.001 inch can be greater than 60 dB. Thus, the ultimate sensitivity of the system approaches 1  $\mu$ in.

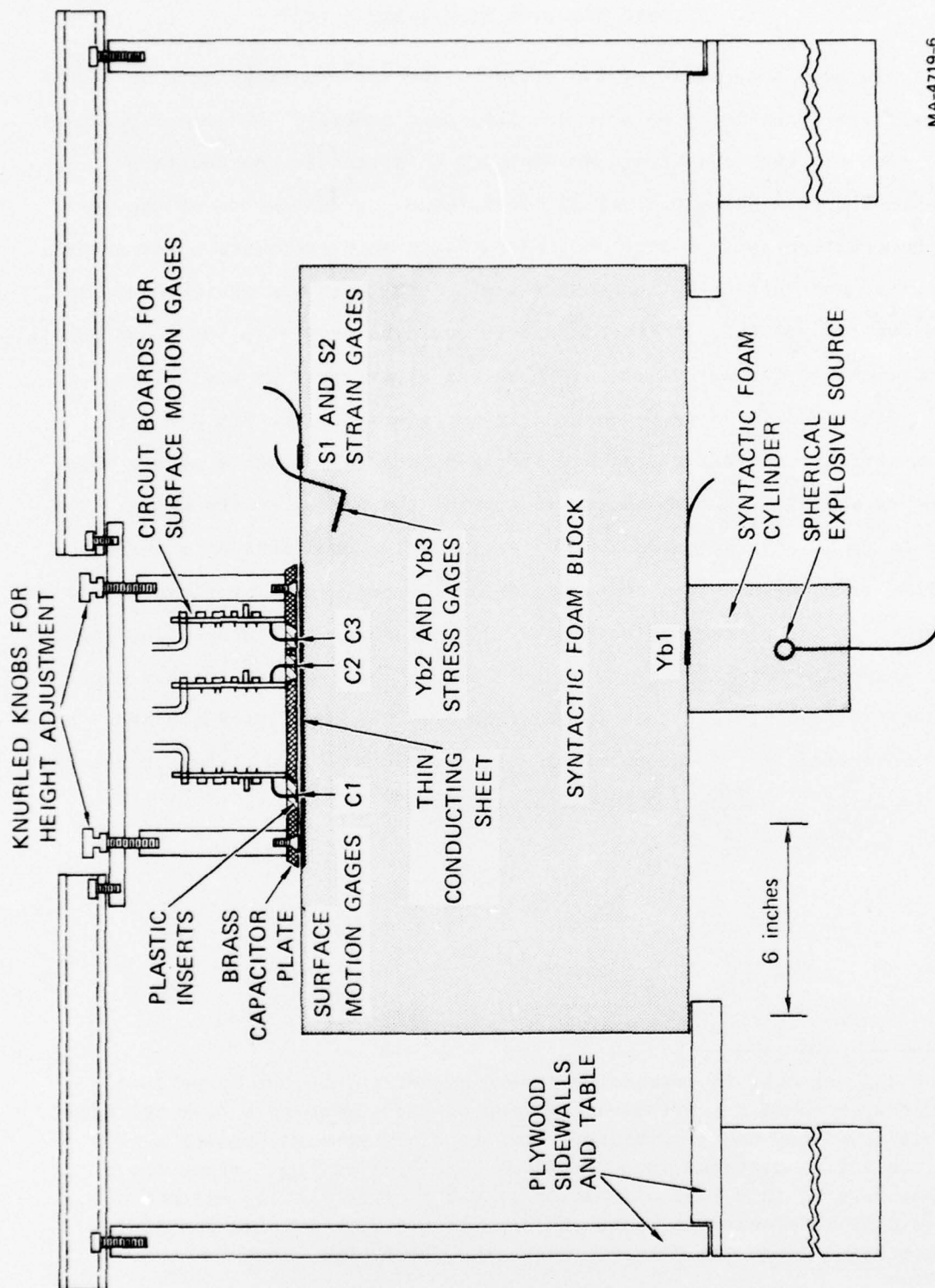
#### IV SEISMIC MODELING EXPERIMENTAL TEST

In the final phase of the project, the various techniques developed for three-dimensional seismic modeling were combined into one experiment to test the entire system. We designed this test to use the large syntactic foam seismic modeling block loaded by detonation of the small spherical explosive source and instrumented with transducers for stress, strain, and surface motion measurements. The test was designed so that as many as possible of its components could be used with the least possible modification for actual seismic modeling experiments in the future.

The test is shown schematically in Figure 3. The 2 x 2 x 1 ft syntactic foam block rests on a strong wooden table with a square hole cut out of it to allow access to most of the bottom of the block. The small spherical explosive source is cast into the middle of a 4-inch-diameter by 6-inch-long syntactic foam cylinder, which is glued to the center of the bottom of the block.\* An ytterbium foil stress gage (Yb1) is encapsulated at this glue line to record the pressure history input into the foam block. This 50-ohm gage of 0.001-inch thickness and approximately 1 inch diameter has been previously used at SRI to measure peak stresses as low as approximately 50 bar.<sup>4</sup>

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\* We did not cast the explosive source directly into the large foam block, because a previous detonation of the source in a foam cylinder had indicated the possibility that shear cracks might travel a substantial distance into the block before arresting. Since the purposes of this test allowed us to use a cylindrically symmetric loading we elected to place the explosive source outside the large block and avoid the chance of damaging the block.



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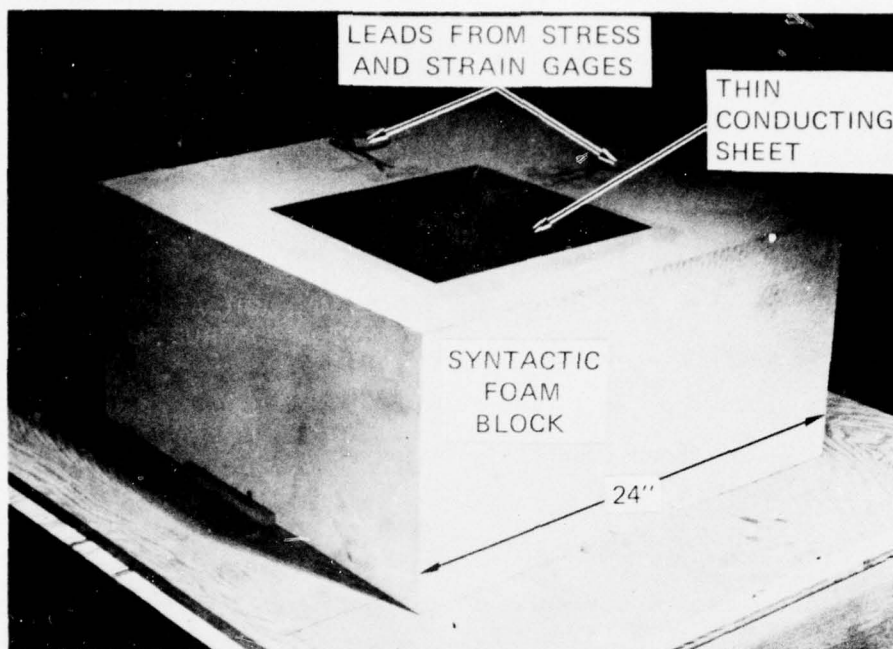
FIGURE 3 SCHEMATIC DIAGRAM OF SEISMIC MODELING EXPERIMENTS

Two additional ytterbium stress gages (Yb2 and Yb3) were placed approximately 1 inch below the upper surface of the foam block and approximately  $4\frac{1}{2}$  inches from the axis of cylindrical symmetry. And two thin foil strain gages (S1 and S2)\* were attached to the upper surface of the block at a distance of 6 inches from the axis, oriented so as to measure surface strain in the radial direction. Because of their positioning with respect to the cylindrical symmetry of the test, the two stress gages Yb2 and Yb3 would undergo identical loading histories, as would the two strain gages. Thus, we would have a check on the precision of these respective transducers under seismic modeling conditions.

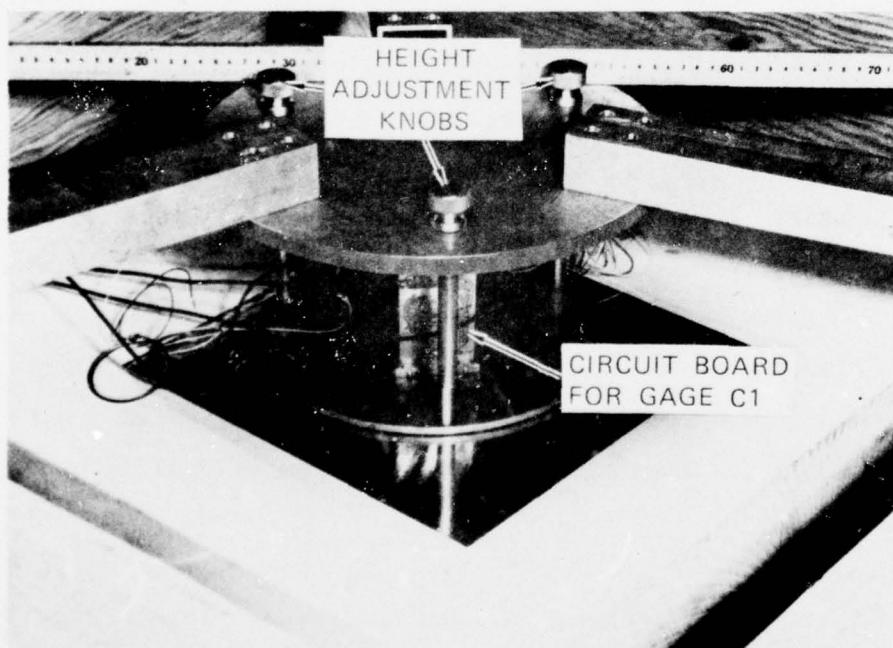
As a first experimental test of our capacitive surface motion transducer system, we placed surface motion gages above the upper surface of the block to measure the displacement history at three points. Two of these gages (C2 and C3) had their centers 0.5 inch on either side of the axis of cylindrical symmetry and a third gage (C1) was centered 4.5 inches off to one side. The stationary plates of the three capacitive gages were thin 0.5-inch-diameter copper disks set into plastic inserts, which in turn were set into a 9-inch-diameter brass disk that acted as the stationary reference plane. The plastic inserts provided a 0.25-inch-wide gap between the gage plate and the reference plane. A 0.001-inch-thick sheet of copper foil was glued to the top of the foam block to serve as the moving conducting plane, and the brass plate with the gage inserts and circuit boards attached were suspended above the block, as shown in Figure 4, from a rigid frame connected to the table sidewalls. Accurate initial height adjustment was provided by three knurled knobs attached to rods with finely pitched threads, so that, with the aid of feeler gages, the stationary reference plane could be positioned very nearly parallel with the moving conducting plane at any desired height.

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\* Type EA-06-250BF-350, Micro-Measurements, Romulus, Michigan.



(a)



(b)

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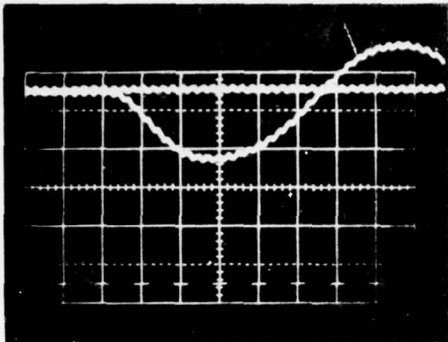
FIGURE 4 SYNTACTIC FOAM BLOCK (a) BEFORE AND (b) AFTER EMPLACEMENT OF SURFACE MOTION GAGE ASSEMBLY

We cast two of the syntactic foam cylinders containing the spherical explosive charges so as to be able to perform two identical tests. For the first of these test shots (Shot 4719-2), we had only a very rough idea of the stresses, strains, and surface motions that would occur, and in order to bracket our uncertainties, we set relatively low sensitivities on our recording oscilloscopes. Posttest inspection of the oscillographs showed that the signals occurred at the expected times, but were an order of magnitude or two lower than the upper limit of the values we expected, so that all the oscillograph traces were nearly horizontal lines.

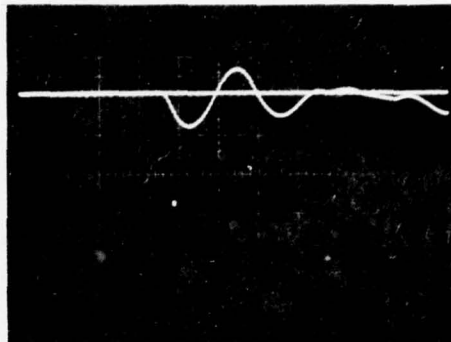
For the second test shot (4719-3), we readjusted our recording sensitivities and obtained records of excellent quality. The raw data for the surface motion gages are depicted in Figure 5, which shows a pretest baseline and the actual shot record from both fast- and slow-sweep oscilloscopes for each of the three gages. The delay given is that between the detonation of the explosive charge and the triggering of the scope trace. cursory inspection of these records reveals a low-amplitude, constant frequency signal superimposed on the records from Gages C1 and C3, but not on Gage C2. A check of the frequencies of the RF carrier signals for the three gages yielded values of 8.75, 11.0, and 8.0 MHz, respectively, for Gages C1, C2, and C3. The frequency of the signal superimposed on the records of Gages C1 and C3 is approximately 750 kHz, which is the difference between their RF carrier frequencies. No such beat signal appears on Gage C2, because its RF carrier frequency is sufficiently different from the other RF frequencies that the beat signal is removed by the low-pass filter.

The records are quiet. Other than the beat frequency discussed above, these records do not show noise of any kind. Therefore, the signal accuracy is limited only by any geometrical distortion in the oscilloscope optics, by irregularities in the width of the scope trace, or by our ability to accurately digitize the record. At these scope settings, the largest uncertainties introduced should be less than 1 mV,

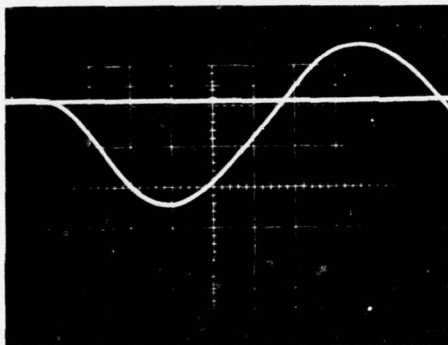
SHOT 4719-3, SCOPE 32, GAGE C1



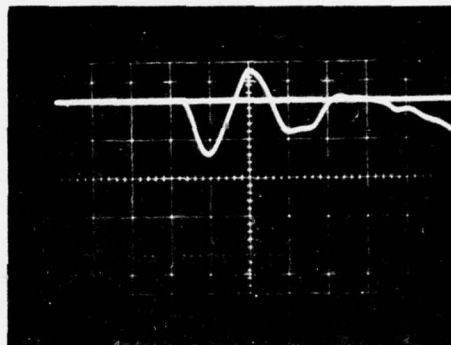
SHOT 4719-3, SCOPE 30, GAGE C1



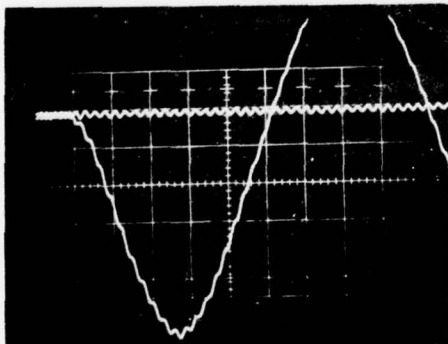
SHOT 4719-3, SCOPE 28, GAGE C2



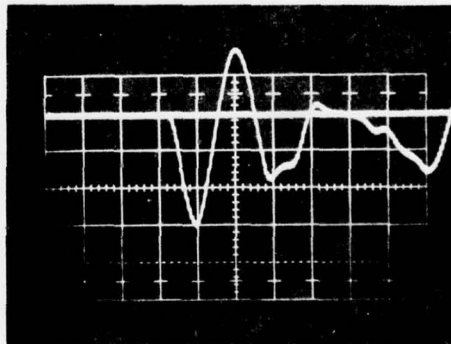
SHOT 4719-3, SCOPE 29, GAGE C2



SHOT 4719-3, SCOPE 33, GAGE C3



SHOT 4719-3, SCOPE 36, GAGE C3



50 mV/cm 5  $\mu$ sec/cm  
160  $\mu$ sec DELAY

100 mV/cm 20  $\mu$ sec/cm  
100  $\mu$ sec DELAY

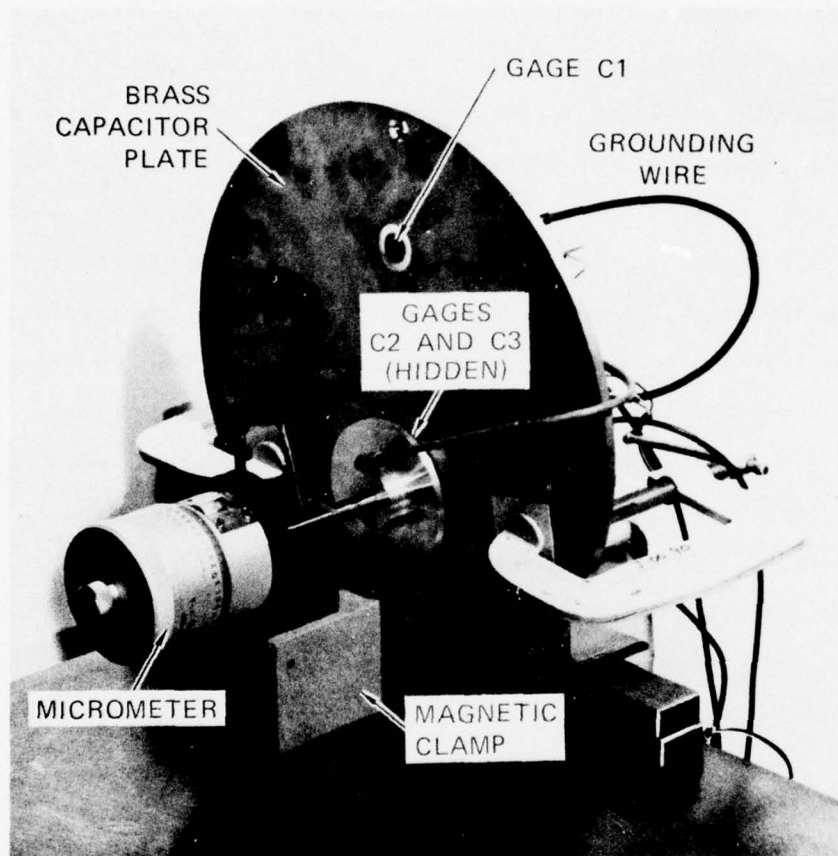
MP-4719-7

FIGURE 5 SURFACE MOTION GAGE OSCILLOGRAPHS

which corresponds to accuracies of better than 1% of the peak value for Gages C1 and C2, and better than 0.33% of the peak value for Gage C3.

To obtain calibration curves for the surface motion gages, we used the setup shown in Figure 6. The brass reference plate with the gage inserts and a 3-inch-diameter plate attached to the spindle of a very accurate micrometer were positioned parallel to each other on a smooth, flat table. The micrometer plate was brought into contact with the reference plate and the voltage output of the capacitive circuitry was recorded at intervals of 0.001 inch as the micrometer plate was displaced with respect to the reference plate. The resulting curves are plotted in Figure 7. Along the horizontal axis is plotted relative distance. Because of irregularities in the surface finish of the plates, we cannot set the distance between the plates to exactly 0 inch, or determine the exact distance between the plates. However, it is not at all difficult to accurately measure changes in plate separation, and this change in separation is precisely what we are measuring in the actual shot. The diamond-shaped point on each curve represents the initial voltage of the gage circuit output immediately before Shot 4719-3. The abscissa of each point thus represents the initial plate separation of each gage, and subsequent changes in output voltage will, by following the calibration curve, determine the gage motion.

The sensitivities of the gages at their initial preshot positions vary from 314 mV/0.001 inch for Gage C2 to 753 mV/0.001 inch for Gage C3. These sensitivities could, of course, be increased to better than 1 V/0.001 inch by reducing the initial plate separation. Since the baseline noise level is  $\approx 1$  mV, we can obtain displacement accuracies ranging from 3  $\mu$ in. for Gage C2 down to 1-1/3  $\mu$ in. for Gage C3.



MA-4719-5

FIGURE 6 SURFACE MOTION GAGE CALIBRATION SETUP

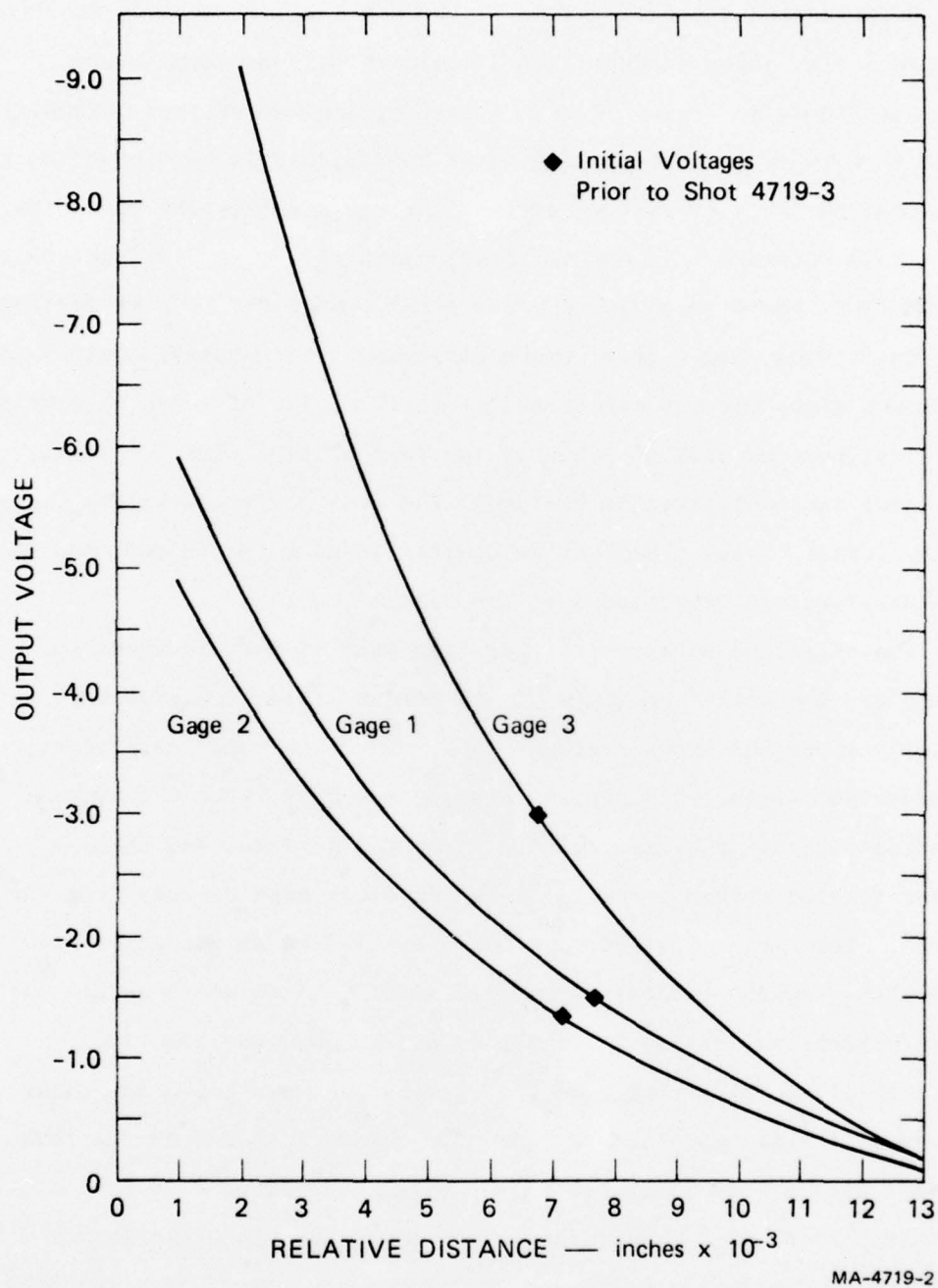


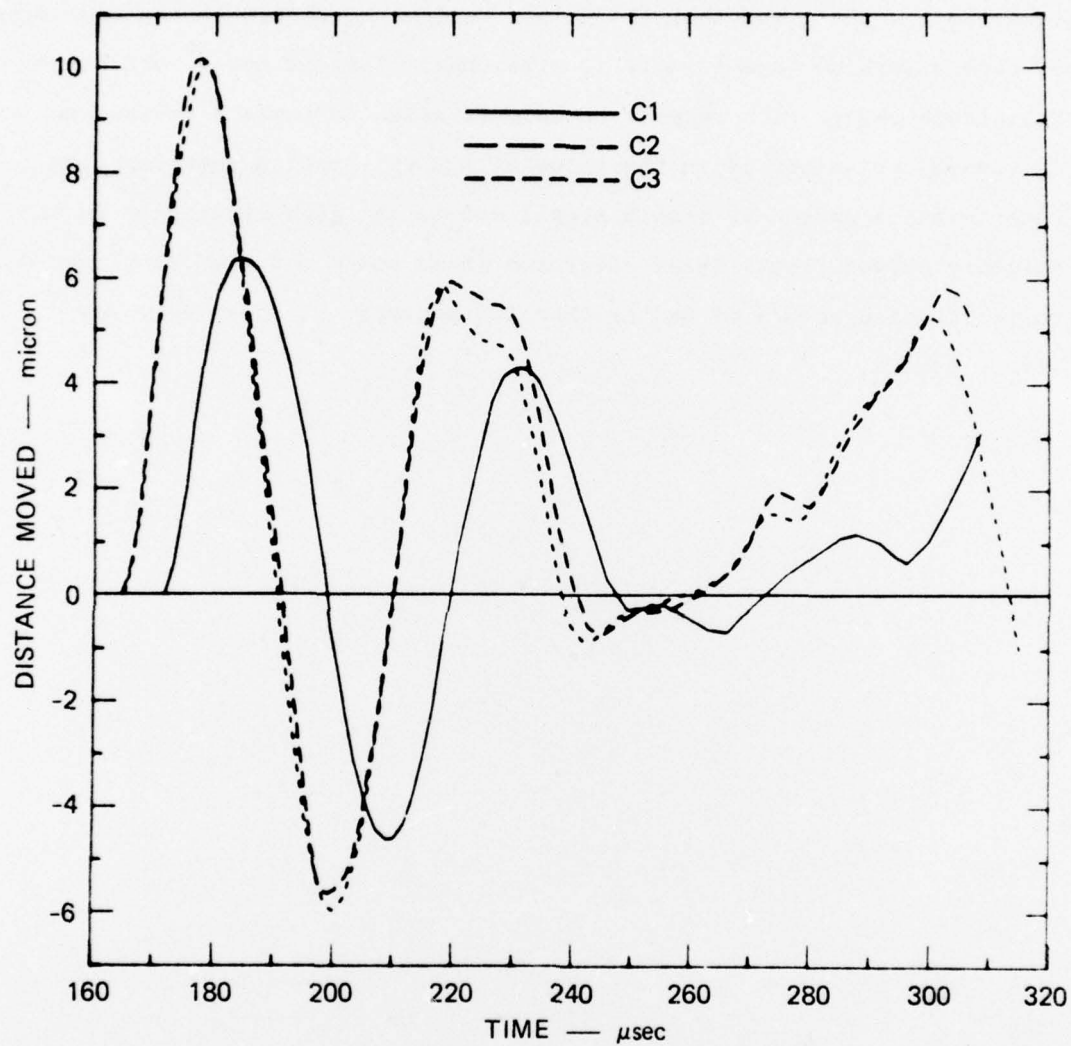
FIGURE 7 CALIBRATION CURVES FOR SURFACE MOTION GAGES

Digitization and calibration of the oscillograph records from the surface motion gages in Shot 4719-3 yield the displacement histories shown in Figure 8. Gages C2 and C3, which, because of their symmetric position with respect to the explosive charge, should have observed identical loading, exhibited nearly identical displacement histories. Their peak upward displacements of approximately  $10\text{ }\mu\text{m}$  (approximately 0.0004 inch) are within 0.5% of each other. Gage C1, located further from the source, has a peak upward displacement of approximately  $6\text{ }\mu\text{m}$ . All three gages exhibit approximately 1-1/2 cycles of vertical ringing until reflections from the side of the foam block arrive (at about  $260\text{ }\mu\text{sec}$ ) to complicate the picture. The peak surface velocity recorded at the center of the block was determined to be  $\approx 120\text{ cm/sec}$ , and the peak acceleration experienced by the surface,  $\approx 10^4\text{ g}$ .

The digitized strain histories from Shot 4719-3 are shown in Figure 9. The active elements of the strain gages were oriented radially along the upper surface; thus, the gages experience first, a compressive strain (with a peak value of  $8.4 \times 10^{-5}$ ) as the initial wavefront travels radially outward along the surface, and then, a larger tensile strain ( $\sim 9 \times 10^{-5}$ ) as the block expands away from the source. The strain histories recorded by the two strain gages are very close together in value, especially for the first  $50\text{ }\mu\text{sec}$ . The peak compressive values, for example, differ by less than 1%.

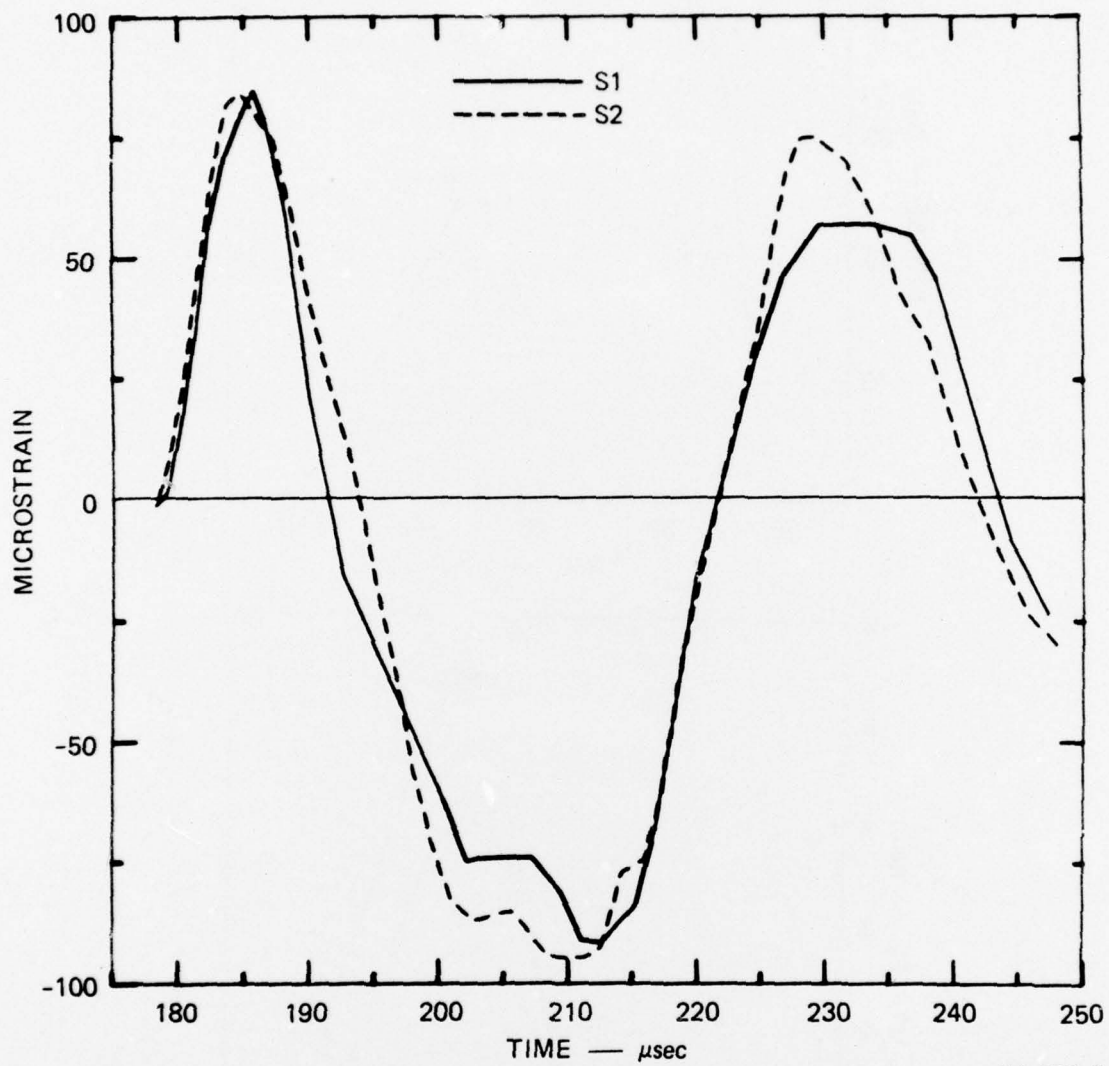
The stress histories from the ytterbium stress gages are shown in Figure 10. The upper curve shows the stress that enters the lower surface of the foam block. It has a peak value of over 40 bars and a half-peak width of  $5\text{ }\mu\text{sec}$ . The lower curves are the histories from Gages Yb2 and Yb3, located 1 inch below the upper surface. The peak stresses recorded by the two gages are 4.0 bars and 5.15 bars, respectively. This significant discrepancy between the two gages is related to the fact that we are at the extreme low end of the stress

level for which this ytterbium gage can be considered practical. The piezoresistance coefficient for ytterbium in the low pressure region (below  $\sim 1$  kbar) is 4% change in resistance/kilobar.<sup>5</sup> The fractional change in resistance corresponding to a stress of 5 bars, therefore, is equal to  $2 \times 10^{-4}$ , and thus the actual resistance change in the nominally 50 ohms ytterbium gage is only 10 milliohms. That is not a very large resistance change with respect to uncertainties in contact resistance in the solder joints or in the value of our calibration resistors, or uncertainties caused by strain signal due to the gage stretching in the slightly curved flow. These ytterbium gages could not then be expected to yield measurements of better than 10% accuracy at these very low stress levels.



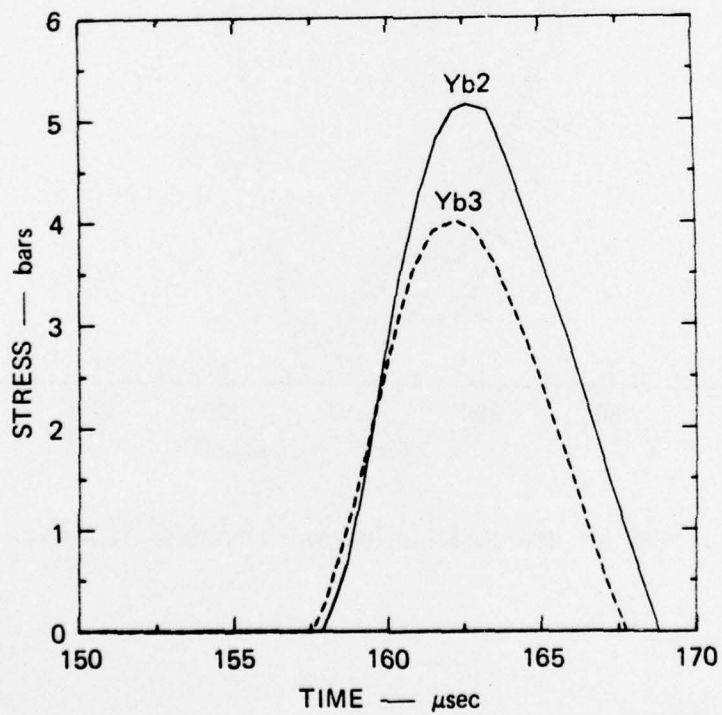
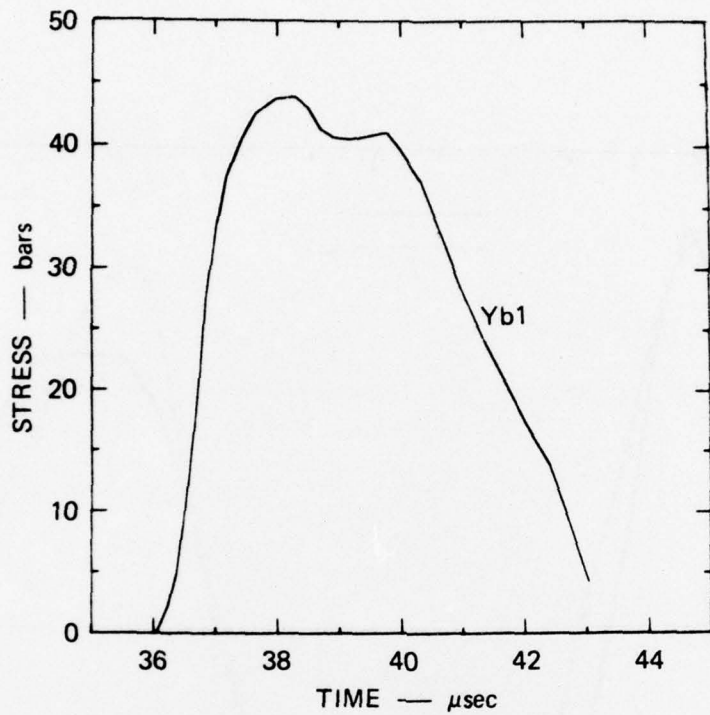
MA-4719-3

FIGURE 8 DISPLACEMENT HISTORIES FROM SURFACE MOTION GAGES



MA-4719-8

FIGURE 9 STRAIN GAGE HISTORIES FROM SHOT 4719-3



MA-4719-1

FIGURE 10 YTTERBIUM STRESS GAGE HISTORIES FROM SHOT 4719-3

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